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THE TROTTER-PATERSON MEMORIAL LECTURE

The Nervous Reactions of the Retina

By E. D. ADRIAN, O.M., P.R.S.

The invitation to give this lecture is too much of an honour to be accepted without hesitation, and, knowing how little I should be able to justify your choice, I ought no doubt to have refused without any hesitation at all. The physiologist at present can give you a great deal of information about the eye, but not much that has a bearing on practical problems of illumination, at all events not much that cannot be found in the textbooks of 50 years ago. I knew this when you invited me, but, although I did hesitate and do feel acutely aware of having no story to tell you, I had to accept an invitation which does honour to the two men in whose memory this lecture was founded. Many of you will have known Sir Clifford Paterson better than I did, but I knew him well enough to like him very much. He was a most able and kindly man, who inspired confidence because he was never trying to impress. He could organise a great laboratory for industrial research and direct its work without ever ceasing to be the unassuming scientist who could reduce complex technical problems to simple terms. He was certainly the friend as well as the director of his staff.

Alexander Trotter was of an earlier generation. Though he died only five years ago, he was born in the middle of the last century and came to the front as an illuminating engineer in the nineties. I did not know him personally, but at least I can claim him as a member of my own College. Trinity had two members of his family in the nineteenth century. His half-brother, Coutts Trotter, came up in 1855 and stayed in Cambridge till his death in 1887. He was a Fellow of Trinity, lecturer in physical sciences, Tutor and finally Vice-Master. He is remembered now for the active part he played in shaping the policy of the College and particularly for his encouragement of natural science. The Trotters were practical men and Coutts Trotter devised one form of encouragement which has been singularly effective. He left a fund to Trinity to be used for a research studentship in Physics or Physiology and in the list of Coutts Trotter students you will find twelve Fellows of the Royal Society with the names of two Presidents, Rutherford and Dale, as holders of the studentship during the first six years of its existence.

Coutts Trotter had become a Tutor when his half-brother matriculated in 1876 and A. P. Trotter was placed under his care. Clerk Maxwell was already Cavendish Professor, but experimental physics was a new Science for Cambridge and in those days the undergraduate who studied it had to be a man of independent outlook who could take pleasure in making instruments as well as in using them. It is on record that A. P. Trotter transmitted speech by telephone across the Great Court in 1877 and he never lost the habit of putting things together and making them work. He became one of the pioneers in the new science of electrical engineering when the chief use of electrical power was for illumination. His papers on lighting are classical. And so our meeting recalls these two men, Trotter, who helped to start, and Paterson, who helped to develop, one of the greatest contributions which science has made to human efficiency and human comfort.

It is in one sense a compliment to the illuminating engineers that we take our comforts so much for granted, that we expect to have all the light we want and think ourselves badly served if we cannot get it. For city dwellers it is difficult to imagine the time when there were perils and dangers of the night for grown-ups as well as for children. It is reflected in the laws of England which make it a far more serious offence

The second Trotter-Paterson Memorial Lecture delivered at the Royal Institution, London, on January 28, 1953.

to steal from a house after dark than in the day-time. Yet the improvement is recent enough. What would our grandparents have thought of the idea of using a total of 100 candle-power to light a study or a bedroom? They lived, of course, when the age of applied science was scarcely under weigh and it has brought many other revolutionary changes which we take for granted, the telephone, the hot and cold taps over the basin and music on pressing a button, but we have had the blackout to remind us of what earlier times must have been like, and when the light came back in the streets we could realise what we owe to your achievements.

I can start by expressing our gratitude for better lighting, for as a physiologist I can only speak about the consumer and how our sense organs make use of the light you provide. But I must warn you that the physiologist spends most of his time explaining why the body works as it does—he can rarely suggest any way of making it work better that has not been tried already by practical people. Also the physiology of the sense organs is not the same thing as the physiology or psychology of sensation. We have learnt a great deal in the last 20 years about the eye, its minute structure, its photochemistry and the signals it sends up to the brain, but most of what we know about human vision is an old story: it could have been found out without reference to the detailed structure of the retina, and in fact most of the fundamental facts about human vision were established in the latter part of the nineteenth century, when our knowledge of the nervous system was rudimentary by present standards.

The same would be true of other forms of sensation and for the same reason. Our bodies are constructed with sense organs to detect changes in the environment and a nervous system to make us react appropriately to them. Sometimes the appropriate action is a fairly simple and immediate adjustment, like turning the head at a sound, or blinking at a bright light. As far as we can tell, that kind of reaction can be adequately explained in terms of physical and chemical changes in the nerves and muscles: it involves a great many living cells, but there is no need to suppose that their activities are on a different footing from those of any other material system. But the nervous system can also carry out adjustments of a different kind, appropriate not only to the immediate circumstances but to needs likely to arise in future, adjustments involving an intelligent plan of action based on memory of what has happened in the past. When these are involved a new kind of activity seems to come into play, for the operations of the nervous system make us, our minds if you like, aware of what is happening. Our awareness is scarcely a physical event like the environmental change that stimulated the sense organ or the train of nerve impulses that signalled the event to the brain. We must leave its nature to the philosophers: but if mental events can be described and measured, the most obvious way of investigating our sensory equipment is to measure them, to use the widest range of stimuli and record what we experience. The physiologist wants to find out all he can about the intermediate links in the chain, the action of the stimulus on the sense organ and of the sense organ on the central nervous system, but the physicist can study sound without relation to the organ of Corti and Thomas Young could arrive at the three-colour theory knowing very little about the nervous organisation of the retina.

Now sights and sounds are the two kinds of sensation which can be investigated most readily because we think in terms of sights and sounds and can measure and describe them almost as though they were material events. Many of the sense organs give no such clear-cut mental experiences: it is difficult to describe and measure pain for instance, and we have many important sense organs which give no sensation at all, because their information is used for the routine business of the body and does not come through to the highest level where consciousness comes in and general policy is decided.

For other animals than man the chief guide to intelligent behaviour may be

hearing, or smell, or even sensation from the whisker or the snout; but for man and monkeys and birds vision is the dominant sense. We are so used to having a picture of the external world as a constant background to our thought that we do not always realise how much we depend on it. In fact most of us depend on it so much that other kinds of sensory information lose half their effect if they are not reinforced by vision. Who wants to smoke, or eat or drink in pitch darkness? If you shut your eyes so that you could listen to what I am saying without seeing me saying it, the inevitable consequence would be that you would soon be fast asleep. Think, too, of the rumoured disruption of the family circle by television. We can all stay inattentive to the most seductive radio programme, but a television screen is far more compelling because it is far more difficult to avoid looking at it.

To be used as they are as our chief guides to intelligent action, visual experiences must be a reasonably faithful record of the visual scene, they must be capable of great complexity and they must be readily analysed, measured and classified. That is why it has been possible to find out so much by measuring the stimulus and the sensation without considering the intermediate terms. But it would be a mistake to suppose that the information furnished by our sense organs is ever a strict mental counterpart of the sensory message. For one thing, information of a change in the environment rarely comes in from one sense organ alone. With the stimulation of the eye by light, there will be eye movements, pupil changes, perhaps movements of the head and compensating movements to keep the balance of the body. These may well add to the overall effect on consciousness. But with vision the chief complication will come in at a much higher level, at the level where the nervous system has developed the plasticity which is its greatest asset in man, the plasticity of the brain which leads to habit formation, to the ability to remember, to pick out familiar features in a new setting, to use past experience as a guide to intelligent behaviour. We cannot see anything without the train of associations which the pattern suggests, the printed word suggested by a few black and white lines. The visual picture will always mean something.

I think it is worth stressing the point that what we see is not merely a faithful reproduction of the pattern of light and shade on the retina, but is an elaboration of it with a good deal of editing by the nervous system, an artist's picture of the visual scene rather than a photograph. All of us have a blind spot in the retina, but the nervous system fills in the picture for us. Still more remarkable is the way in which it will produce a continuous picture, even though considerable areas of the retina have been put out of action by disease. If the entire visual pathway on one side is thrown out of action so that the left or right half of each retina is blind, we are not aware of the loss of half the visual field. We do not see so well, but we seem to have as wide a view as we had before.

The fact is that the nervous system deals with the picture thrown on the retina as the editor of a newspaper would do. The important information is underlined, perhaps exaggerated and given a more definite twist, and it is presented to the brain as clearly as possible, whereas the unimportant details and the gaps left by any deficiencies in the reporting system are put into the background so that they can only be found if a special search is made for them—as it has to be made to show us our blind spots.

It is not only visual information which is treated in this way. The nervous system feeds the brain with a summary of important items of news of all kinds and in every case the information which finally reaches consciousness is made into a consistent story by leaving out irrelevant details and making the best use of whatever the sense organs can supply. News should deal with new events, the changes rather than the steady background, and so for the purposes of the brain the sensory

system is more concerned with changes in the stimuli which reach it than with their absolute value.

It is true, of course, that the nervous system does not exist for the sole purpose of feeding the mind with a summary of important news. It has to provide the data on which all the humbler office work of bodily control is carried out and this may need sense organs which will give continuous signals of a constant level of stimulation. At all events some of them do, the temperature organs in the skin for instance and the stretch receptors or tension recorders in the muscles. But with all sense organs, and indeed with living cells generally, there is always a tendency to come into equilibrium with new surroundings and therefore to react much more when they are actually changing than when they have changed and to react more to a change that is abrupt than to one that is gradual. In greater or lesser degree, therefore, we should expect that at every stage on the way from the eye to consciousness the emphasis would be on the new items in the visual pattern. To keep the stable items before us, we must be constantly refreshing the picture by shifting our eyes from one point to another and in animals where vision is the dominant sense the eyes are rarely held for long on one point.

This is a very long introduction to the physiology of the retina, but it is important to underline the role of the nervous system in presenting visual information, for it has become one of the chief growing points of the physiology of vision. It has come to be so mainly from an increased knowledge of the complex nervous structure and nervous activities of the retina. The complex structure is an old story, but it has gained interest from the newer story of the complex signals which go from the retina to the optic nerve.

Of the sensitive elements in the human retina 95 per cent. are rods, over 100,000,000 of them, leading to the 500,000 fibres of the optic nerve by converging pathways linked together by cross connections in the retinal network. With the 3,000,000 cones there is less convergence, and those in the fovea, where we see most acutely, are credited with a single optic nerve fibre apiece instead of one to a hundred, but over the rest of the retina they are less favoured and some may share an optic nerve fibre with a group of rods.

If the retina were no more than a fixed distributing system with each group of receptors connected to the brain by a single nerve fibre, the effect of the convergence would be merely to enlarge the receptive area for each transmitting line. We should have to think of the surface as made up of unit areas ranging in diameter from that of a single cone up to that of a group of several hundred rods. But the existence of cross connections in the retina makes it difficult to draw any clear line between one receiving unit and the next. In travelling from the sensitive element, rod or cone, to the optic nerve the signals must pass through two regions where interaction might occur. They must be handed on from the receptor cell to a bipolar nerve cell in the retina and from that to the ganglion cell which sends out the optic nerve fibre. Now the transference of a signal across the gap between one nerve cell and another, the synapse, is rarely as simple and inevitable a process as the transference of a signal down an unbroken stretch of nerve fibre. There is always the chance that it will be modified in passing the gap and that the cell on the far side will be open to other influences as well. In this case the chance is made far more likely by the existence of two layers of nerve cells with processes running out laterally, one linking the bipolar cells together and the other the ganglion cells. Some of these horizontal cells send their branching connection over a distance of a millimetre or more. Their presence does not prove that signals from points 1 mm. apart on the retina can influence one another, but it provides a means for them to do so.

It is fifty years and more since Cajal worked out the nervous pathways through the retina, but the evidence of what comes down them is much more recent. It comes from records of the electrical activity in the optic nerve fibres. The signals

which pass to and fro in the nervous system by way of the nerve fibres are all made up of repeated brief impulses, momentary bursts of activity with a sudden surface change allowing ions to move in and out of the fibre. The surface change sweeps along the fibre and as each region becomes active the ionic movement sets up a difference of potential between it and the inactive region beyond. So by recording the potential between two points on the fibre, we can tell each time an impulse passes down it and we can study the messages made up of impulses repeated slowly or rapidly.

To use the method successfully for investigating sensory messages we must be able to detect the action potentials in the individual nerve fibres. Technical difficulties may prevent this and so far they have prevented all attempts to record the initial stages in the visual signalling, the signals which travel from the rod and cone elements through the outer layer of the retinal nerve cells. But the fibres of the optic nerve and the cells which supply them are more accessible and from them we can record the signals which emerge after they have passed through the nervous apparatus of the retina. We cannot, of course, do this with the human eye and so far most of the evidence has come from the eyes of animals which have far less use for the particular kind of visual information on which we rely. Man needs detailed and coloured pictures in bright light, whereas a cat's eye is probably used more often for detecting slight movement in half darkness. But the same structures are present in most mammalian eyes and if we leave colour vision out of account for the moment we can be reasonably sure that the signals from the receptors will be dealt with in the retina in much the same fashion.

In many ways records from the optic nerve fibres are what we should naturally expect. Lighting the retina starts a discharge of impulses in the fibres of the optic nerve and the discharge increases with the intensity of the light. Any movement of light and shadow across the retina gives an immediate response in the nerve and so on. One thing our own visual experiences would not lead us to expect and that is what is known as the off discharge. With most of the vertebrate eyes so far examined turning off the light gives a discharge of impulses as great as, or greater than, that given by turning it on. Granit has found that some of the optic nerve fibres signal only when the light goes on, and some only when it goes off, and some signal both events. The proportion varies in different animals and though I am speaking on the basis of very few experiments, my impression is that the off discharge is much less in the eye of the monkey, with daylight vision like ours, than in the eye of the cat. At all events if we had nothing but the optic nerve signals to guide us we should conclude that the cat sees mainly darkness and the monkey mainly light, although both eyes react to some extent to a change in either direction.

The off discharge was noticed in the first experiments of this sort that were made, but the eye which showed it was even less comparable to ours than that of a nocturnal mammal. It was chosen entirely for the length of the optic nerve and this happens to be very long in the conger eel. The conger eel's eye had few other advantages, but the records made from the nerve besides showing the off discharge were enough to prove that the pathways through the retina were not entirely independent of one another. It was found, for instance, that if two points on the retina less than 1 mm. apart were lit simultaneously the discharge in the optic nerve occurred much sooner than if one or the other point was lit alone, and the distance over which this interaction would occur was found to vary with the state of the retina and so could scarcely have been due to a fixed convergence of pathways from receptors a long distance apart.

Since then far better and more detailed studies of the optic nerve discharge have been made by Hartline in America and by Granit in Sweden. We know now that

the nervous connections in the retina do not merely allow two bright regions to reinforce one another, they can also work the other way, suppressing or inhibiting one discharge in favour of another; and for all we known such reinforcements and inhibitions may take place at other relay stations in the visual pathway and not only at the level of the retina.

On their way up to the cerebral cortex—and so to the mind—the impulse messages from the retina pass through another nervous structure where such transformations may well occur. It is a region known as the medial geniculate body and it has several layers of nerve cells arranged in sheets much as they are in the retina. We know very little about what goes on there, but I mention it because Professor Le Gros Clark has the interesting theory, based on its structure, that it may be the chief sorting station which is needed for a full range of colour vision.

It would not be too difficult to record the visual signals at various levels from the retina up to the cerebral cortex, but it is easier to pick out the single cells or nerve fibres before they have entered the brain stem and at present most of our data come from the optic nerve level. The difficulty is not so much in making records of the visual signals but in interpreting them, using them to draw conclusions about vision in general or human vision in particular. The data from one sort of nerve fibre in one sort of animal may not be a fair sample, for we tend to select the units which give large potential changes in the recording system. Again, the eyes of different animals vary considerably in the reaction of the retinal mechanism to light of different wavelengths. To realise this, we have only to record the electroretinogram, the potential differences which are developed between the cornea and the back of the eyeball when the eye is exposed to a brief flash : in animals with good daylight vision, birds, monkeys and men, orange or red light gives a deflection which is missing or very small in the eye of a cat or rabbit, the animals most often used for investigating the nerve signals.

But in spite of these uncertainties, we have enough data from the optic nerve discharges to be sure that there is a good deal of interaction in the retina. It does not behave at all like a recording screen with a mosaic of sensitive areas each leading by an insulated pathway to the brain. That may be true of the fovea where there are no cross connections, but everywhere else the stimulation of a single element will have an effect which is not confined to a single track but is spread out over the neighbouring tracks leading from the surrounding elements.

The nature of this effect is not always the same, nor is the distance through which it spreads. Hartline has found that a large area brightly lit will suppress the signals coming from neighbouring areas, whereas if the retina is in darkness the feeble illumination of one point will reinforce that of another some distance from it. Thus in bright light the contrasts between light and dark areas will be exaggerated and in semi-darkness perception of form will be sacrificed to perception of light. The eye has, of course, a variety of means of adjusting its sensitivity to the level of illumination : in bright light the pupil contracts, the visual purple is bleached and in some eyes the cones shorten and a curtain of pigment cells descends on the rods. To these we can now add the possibility that the interaction of nerve cells in the retina may change in degree or in sign, darkness favouring mutual summations over wider and wider areas and light converting the effect to inhibition.

Here I am running some way ahead of the evidence which we have gained from records of the optic nerve messages, but there is supporting evidence from an entirely different source. I said at the beginning that most of the important evidence about vision dates from the last century, when the most fruitful method was to relate the stimulus to the sensation without much regard to the intermediate steps. But some of it was not much noticed at the time, because its interest lay chiefly in relation to these intervening events and this fate seems to have overtaken some observations which Abney made in 1897. His work on photometry and colour vision is, of course,

well known, for he was one of the pioneers like Trotter, though more concerned with the science of seeing than with that of lighting, but his work on the effect of area on the visual threshold is seldom mentioned. He measured the illumination needed to make a white patch on an otherwise black screen just visible to the dark-adapted eye and found that within limits the larger the patch, the dimmer the light needed to make it appear. The effect was already known and it has been investigated by various methods, but Abney's paper remains the best account of it. He found it for areas giving an image up to 0.6 mm.^{2} on the retina. For smaller areas the threshold intensity rose as the area was reduced, so that the total quantity of light falling on the retina (the product of area and intensity) was approximately constant. For areas above 1 mm.^{2} on the retina the total quantity of light increased until eventually a further increase in area made no difference to the threshold for visibility.

Now an area of 0.6 mm.^{2} on the retina must contain many thousand rods and must lead to well over 100 fibres of the optic nerve. Converging connections alone would account for a summation of stimuli over the territory connected with a single pathway, but a true interaction between pathways would be needed to give such precise integration over so many receptor elements. No doubt there are variations between the different units and with some the effect may be more localised to definite pathways. Abney could judge the shape of the patch when the light falling on it was very little more than the threshold quantity but further reduction made the outlines disappear and although he could still see something he could no longer tell its size or shape. It may be that as the light increases the sheets of nerve cells no longer act as a general collecting net for signals over a wide area, but begin to develop the local peaks and troughs of activity which make a detailed visual pattern. At all events Abney's finding shows once again that at low illuminations the visual apparatus does not behave in the least like a mosaic with each sensitive point connected by a private line to the brain. Instead it behaves as we might expect a part of the central nervous system to do, with a remarkable power of making the best of its material. If there is so little light that its effects over the whole area must be summed up to be perceptible, then they are all summed up to make us aware that there is a little light somewhere. As soon as there is enough light for local effects to come through without reinforcement, the brain receives a pattern of signals giving the shape of the lighted region and, when the light is intense, the pattern is still preserved because the contrasts are emphasised.

Abney's experiments were not the only ones to show that the visual picture is not a mere copy of the picture on the retina. There is, in fact, a vast literature dealing with the many kinds of induction which can be observed, though the work of that period was mostly aimed at establishing one theory of colour vision or another. Colour has always remained the centre of interest in experiments with human vision; its charms have not grown less with age and its problems are not abated. The complex areal effects, contrasts, summations and inhibitions which can be observed with colour would only complicate the argument, for in most of the experiments which can be made with human sensation as material there is very little to show where its elaboration takes place. That is where the method of recording the visual signals comes into prominence. We can now be fairly sure that some of the elaboration takes place in the retina. It has a nervous structure which would make interaction possible, the optic nerve discharges show it occurring up to distances of as much as 1 mm. on the retina and our own visual sensations are there to correspond.

What has all this to do with the science of illumination? Very little at present and perhaps not much when we know far more about the physiology of the visual pathways. One thing it can do is to remind us that our visual apparatus has been handed down to us from animals unaccustomed to artificial light. Nowadays

occasions arise when it might be a convenience if we could avoid some of the interactions which make the whole visual system into an organised unit. In driving a car at night, for instance, it might be a convenience if we could keep one eye dark-adapted to see the cyclists and the other light-adapted to see the oncoming cars, but no doubt for monkeys it is more important to have both eyes working in exact conjunction all the time and although the state of adaptation of one eye does not directly affect that of the other the nerves which control the pupil do not work independently, so that a bright light in one eye will certainly reduce the sensitivity of the other.

Our visual apparatus was not built for artificial lighting and we are unlikely to be able to improve the working of our sense organs as long as they are in a healthy state. You may remember at the start of the war when the vitamin enthusiasts urged us all to eat carrots to improve our night vision. Carotene and Vitamin A will certainly improve the visual purple system if it has been impaired by the diet of a concentration camp, but few healthy people did better in the blackout because of the carrots they had eaten. On the other hand, a great many of us learnt to put up with the dark and those who did it best were the countrymen brought up in places where the night is far darker than in a town. Their visual acuity was no better, nor was their rate of dark adaptation, but they saw better in the dark because they knew what to look for and how to interpret what they could see. In fact, although we may not be able to improve the sense organ, our brain can learn to make more use of the signals it receives.

The chief conclusion then is the rather obvious one that from the user's point of view the science of illumination has to concern itself not only with the sense organs but as much with the final stages when the edited picture is presented to consciousness. The impression it makes on us and the use we can make of it will depend not only on its immediate content but on all the associations it calls up, the habits we have formed ourselves or those imposed during the evolution of the human brain. It is natural to dislike a lamp which makes us look like corpses and if we have unaccustomed sensations, lights which flicker or lights which leave out part of the spectrum, we may react as we should do to sugar on a boiled egg instead of salt. The inability to distinguish the full range of colours is not in itself unpleasant if we are used to it—about 4 per cent. of those who are here are probably colour-blind without disliking the colouring of their visual picture, but a sudden change in the colouring is bound to be disturbing until we have learnt to expect it.

How our nervous system learns new habits is still one of the major problems of physiology. We can tell you that it is a highly adaptable organisation and we can point to some of the ways in which it builds up the visual picture. But what we shall like and what we can tolerate when the picture is presented by artificial lighting involves all sorts of factors which cannot be analysed as yet in terms of nerve cells and signals in nerve fibres. Until we know far more about the activities which take place at the highest level, in the brain, we must leave aesthetic considerations to the psychologist, or we must decide them by the time-honoured method of trying out the new way of lighting and seeing whether we like it or not.

The Colour-Rendering Properties of Fluorescent Lamps and a Proposed New Method of Specification

By S. T. HENDERSON, M.A., Ph.D. *(Member)*,
and D. T. WAIGH, B.Sc. *(Member)*.

Summary

To express the colour-rendering properties of light sources, a band system of presenting the spectral energy distribution has been used. The best known example of this is Bouma's eight-band system. In this paper Bouma's method of treating the problem is criticised, and the uses and drawbacks of band systems discussed. The next stage of condensation of information on spectral energy distribution leads to single figures of merit to measure colour-rendering properties. Related to this is the present proposal for expressing a single feature of colour-rendering behaviour of fluorescent lamps, namely the red-rendering efficiency, as an index which will distinguish easily between lamps of the "high efficiency" and "high fidelity" types. It is based on the ratio of energy output at two selected wave-lengths, compared with the ratio for a black body or "Planckian radiator" of near or identical colour appearance. Various methods of determining the index are discussed, varying from a calculation based on spectrophotometry to a direct meter measurement. Data are given for a wide selection of lamps.

(1) Introduction

The importance of the colour-rendering properties of light sources became evident with the introduction of discharge tubes for illumination. One of the major contributions to the subject[1] antedated the wide development of the fluorescent discharge lamp, but there have been numerous later attempts to treat the problem in a way that would give guidance to users of the new light sources. It is the purpose of this paper to comment on some of this work and to suggest a simplified method of classification, particularly for fluorescent lamps, which appears to have some utility for specification and testing purposes. The new proposal has a very limited aim, but it avoids some of the drawbacks of earlier methods.

All necessary information about the emission of a light source, including its colour-rendering properties, is implicit in its spectral energy distribution (s.e.d.) curve. Interpretation of the curve by inspection is not easy, and it is also necessary to have a standard of excellence for comparison. In practice this standard is usually a Planckian radiator or "black body," partly because its properties are easily defined, partly because sources close to this type have been the only ones available till recent years. The problem arising is the derivation of some fairly simple method of assessing the colour-rendering properties of a lamp from the s.e.d. curve. The method must be adequate for specification and any other possible uses, even though any such simplification or condensation will reduce the amount of information conveyed by the complete curve. This paper is not concerned with methods based on Munsell or Ostwald colour patterns, or involving subjective tests.

(2) The Band System

The general principle involved is the division of the visible spectrum into n bands, the percentage of the total energy or luminance in each being derived by

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direct measurement or by computation, with a final presentation of n numbers expressing these values in order instead of the complete s.e.d. curve. This method of abbreviating the information contained in the curve has been widely advocated, particularly in the form of the eight-band division of the spectrum devised by Bouma[1], [2].

(2.1) Bouma's System

Bouma's work, though much quoted, seems to have been little studied. It is unfortunate that it was done before the extensive development of the fluorescent lamp could be foreseen, and so the standard adopted was a filtered incandescent source (Source C). To-day it is the fluorescent lamp which provides most colour-rendering problems, and its peculiar features cannot be ignored. Bouma's pioneer approach to the problem was valuable, but it is right to examine it critically at the present time, for the subject is one requiring a sound basis for future development.

Granted that Bouma produced a workable system, his treatment[1] has, at first sight, a number of unconvincing features. It gives some of its important evidence in the form of deductions from the calculations, but not the details of these calculations. Thus, in the determination of the best way to divide the spectrum, the work on Source A is merely stated to give "analogous results"; in the determination of tolerances, there is no explanation of how the calculations deal with the hypothetical pigments reflecting light in two bands only; and as a third example may be quoted the work on the 16 real pigments, whose varied behaviour under a light-source has apparently been combined into a single set of tolerances for the eight bands. The arbitrary choice (i) of a unit of colour shift in the general argument on colour rendering (0.01 on Judd's U.C.S. diagram), and (ii) of the factor P (1-3), by which the calculated tolerances in the bands have to be multiplied for practical purposes must also be noted.

The main argument presented by Bouma leads to an optimum division of the spectrum of Source C. The divided spectrum, first converted to units of luminance, is concentrated into a line at the mean wave-length of each band. Computation of the resulting chromaticity of the imaginary line spectrum, after reconversion of luminance values to energy, gives values differing from the original chromaticity of Source C. From a number of varied divisions of the spectrum, the familiar eight bands are chosen as giving the least change in chromaticity. On this—the real essence of the paper—it is a fair comment that the exact chromaticity of the source is irrelevant to its colour-rendering properties. It is well known that two fluorescent lamps of identical colour appearance but with different colour rendering can be made, and the converse is also true within limits. Again, the details of the chromaticity changes seem inconsistent simply from the computation aspect: for example, the division of a band into two gives worse agreement (P, eight bands, including one at 4,600-5,100 A, and R, nine bands differing from P by having two bands 4,600-4,800 and 4,800-5,100 A); also 15 equal bands of 213 A width give a worse result than nine, in which the narrowest bands are 200 A and several 500 A wide. The chromaticities estimated from the published diagram are:—

C (Source C)	$x = 0.3100$,	$y = 0.3165$
P (eight bands)	.3105	.3135
R (nine bands)	.3125	.3090
15 bands	.3080	.3085

Some of this work has been repeated, and Bouma's results have been confirmed for the points C, P and R. The discrepancies, therefore, depend on the peculiar energy distribution in Source C. This is a serious objection to its use for the basis of the spectrum division, even if the colour appearance criterion were valid, which it is not.

The distribution in Source C also seems to be responsible for the necessity of

narrower bands at the blue end of the spectrum in Bouma's system. Fluorescent lamp spectra are, however, usually dominated in this region by the mercury lines at 4,047 and 4,358 A, and can hardly require such fine subdivision into bands. The present tendency among users of the band system is, in fact, to combine the blue bands in the interests of simplification[3], [4].

An interesting point arising from the present authors' calculations is the difference between the use of luminance and energy. The shift on the chromaticity diagram from the location of Source C is roughly doubled by the change from eight to nine bands, as shown in Bouma's results quoted above. But by the shorter computation using energy values instead of luminance, the shifts are bigger and in the reverse sense (increased instead of decreased y). The point for eight bands is now twice as far from the chromaticity of Source C as the point for nine bands, which certainly seems more reasonable.

(2.2) Use of the Band System

Although derived in a manner which may be criticised, the eight-band system deserves examination with regard to more practical aspects. Other band systems have been developed, and will be briefly mentioned later, but Bouma's has been the most extensively used. Its derivation for a lamp requires spectrophotometric equipment to give the s.e.d. curve, from which the luminance in the bands may be computed. This procedure has been shortened, though at the expense of more complicated apparatus, by Harrison's divided selenium photocell method[5] and by the mask technique of van Alphen[6], and of Winch and Machin[7]. The results, expressed as a histogram, suffer from the known inadequacy of luminance as an expression of colour-rendering properties, especially at the ends of the visible spectrum where the bands have an importance in colour rendering out of proportion to their small luminance values. The conventional use of a logarithmic luminance scale, while giving a diagram which more accurately suggests the effects of the different bands, is unsound in that the zero level cannot be shown. It is not unreasonable to show the bands as of equal width, even though they cover different spacings in wave-length or frequency, but an obvious practical defect in the band division is that band six covers a comparatively wide range of colour, from green to orange. Other band systems have avoided this. Taylor's[8], using equal numbers of colour steps in the bands, and energy instead of luminance, is one example. Jerome and Judd's ten bands of equal luminance[9] provide another.

The band system histogram has been used to give a general impression of the spectral luminance distribution of fluorescent lamps, with rough comparisons with other light sources. This use is largely a qualitative one, and has some value for advertising and semi-popular descriptions. There are three other possible applications for the exact quantitative data, namely :—(i) Lamp and lighting development projects; (ii) Factory production of lamps; and (iii) Specifications for lamps.

The research worker on phosphors or lamps does not, in the authors' experience, find much use for the abbreviated information in a band diagram when the whole s.e.d. curve gives so much more, including the separate contributions of phosphor and mercury lines. With regard to estimation of probable colour rendering by means of a band diagram for the lamp, together with that of a standard (say, natural daylight), great care would need to be taken to ensure that results were not biased by the choice of band width and location. Use of the band system has been attempted by dyers interested in the closeness of match of "metameric pairs" under similar illuminants, but complete s.e.d. curves would give more accurate information. At present the direct experimental approach to colour-rendering effects seems more

profitable, though a method of measurement somewhat related to the band system is developed later in this paper.

In factory lamp production the band system is of no importance. By the time a predetermined mixture of phosphors is in use for coating lamps the colour-rendering properties are fixed, and cannot be varied without major changes in the phosphor mixture, which would probably cause large chromaticity variations. The slight colour-correcting additions made to the coating material are essential to maintain uniform colour appearance between batches, but can have no appreciable effect on the colour-rendering properties.

Finally, there is the question of specification, which perhaps offers the best outlet for information of the kind contained in band data. The determination of tolerances in the separate bands has proved difficult, as Bouma's work indeed suggested. It is undesirable that the tolerances should merely express the inaccuracies inherent in the measurements, or that they should be so large that lamps of widely differing colour appearance can fall into a single group. A too rigid specification, on the other hand, will enforce the use of certain phosphors, to the possible exclusion of alternatives that might be quite satisfactory in practice. These difficulties may be overcome, but the complex nature of colour-rendering phenomena discourages hope of any early solution.

A major requirement in the use of a band system is a standard of excellence for comparison. This standard should be independent and permanent. If physical measurements are desired it could be Source A, B or C([4]), though the filtered sources have defects referred to in Section (2.1) above. A better theoretical standard would be a full radiator at an appropriate temperature([9]). It is certainly undesirable to use existing fluorescent lamps as standards (Ref. 10, Fig. 6).

As a conclusion to this discussion, Bouma's own comment still seems valid: "It is, however, not very easy to obtain directly from these data a good idea of the differences in colour rendering shown by two light sources "([1]). The viewpoint of the protagonists of the eight-band system has been summarised by Winch and Ruff([10]).

(3) Index Numbers

Attempts have been made to summarise further the spectral emission information and produce a single figure indicative of the colour-rendering properties of a lamp in relation to some standard source. Some of these index numbers do not treat the spectral data directly, but use the colour appearance of selected patterns under the light sources. For example, Jerome and Judd([9]) have discussed the "duplication index" derived from metameric pairs of colours, and Barr, Clark and Hessler([11]) have examined the use of Munsell colours. These methods are too complicated to use for routine checking of light sources. Harrison([3]) has summarised the eight-band data into an overall "figure of merit," combining the "colour contrast factors" for red, green, blue-green and blue with respect to yellow, i.e., bands 7 and 8, 5, 4 and 3 respectively in relation to band 6; a standard source is also introduced to allow comparison of different lamps. There is reasonable correlation between the "figure of merit" and the "duplication index," and this may be improved by a slightly different calculation used by the present authors. The factors in this modification are obtained for red, green and blue against yellow, i.e., bands 7 and 8, 5, and 1 to 4 respectively in relation to band 6. Both versions of the figure of merit fail to distinguish between the "Daylight" and "Natural" lamps used by Harrison though the "Natural" lamp was designed to have improved colour rendering.

Overall index numbers attempting to express the complicated information in a s.e.d. curve by a single figure, must often fail to distinguish dissimilar lamps. Harrison's contrast factors seem to have more value, and the index proposed below is in effect one such factor.

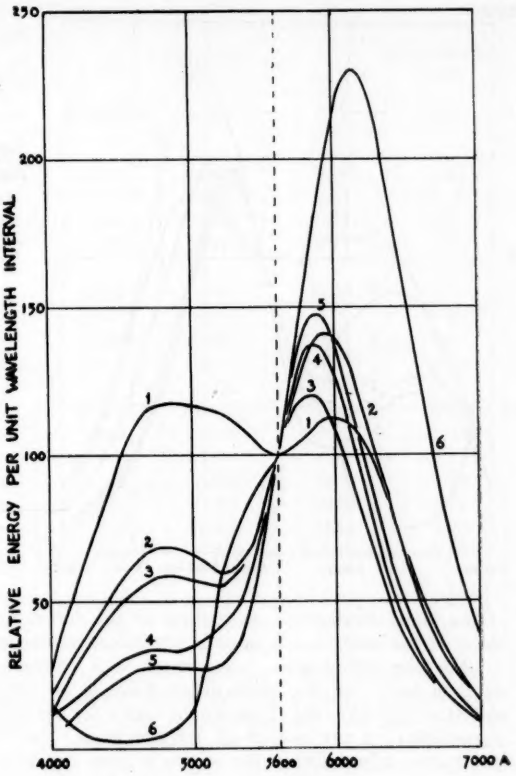

Fig. 1. Spectral energy distribution of fluorescent lamps ; mercury lines are omitted.

1. *Northlight*
2. *Natural Daylight*
3. *Daylight*
4. *White*
5. *Warm White*
6. *Peach*

(3.1) Red-Rendering Index

If the problem is severely limited, results of some value can be obtained for fluorescent lamps of current manufacture by comparatively simple means, as follows. The lamp is compared with a full radiator of the same chromaticity or, if the lamp chromaticity does not lie on the black body locus, the comparison is with a full radiator having the same x as the lamp. The advantage of this condition is that sources of close or identical chromaticity (but, of course, independent colour-rendering properties) will be compared. Since present-day near-white lamps invariably have adequate emission in all parts of the spectrum except the red end, and therefore show marked differences mainly in respect of red colour rendering, this feature alone is considered in deriving an index to express lamp performance. It may be called the "Red-Rendering Index." For most lamps the s.e.d. curves are similar in the region of 5,500-5,800 A, where a rise to a peak of yellow or orange emission near 6,000 A is found, as shown in Fig. 1, where a range of lamps is shown on the basis of equal energy output at 5,600 A. A wave-length in this region is taken for comparison, and a second wave-length in the red region where lamps differ in their s.e.d. curves. The ratio of red to yellow-green energy values is divided by the same ratio for the appropriate full radiator, and the required index is the result. It is in effect the redness

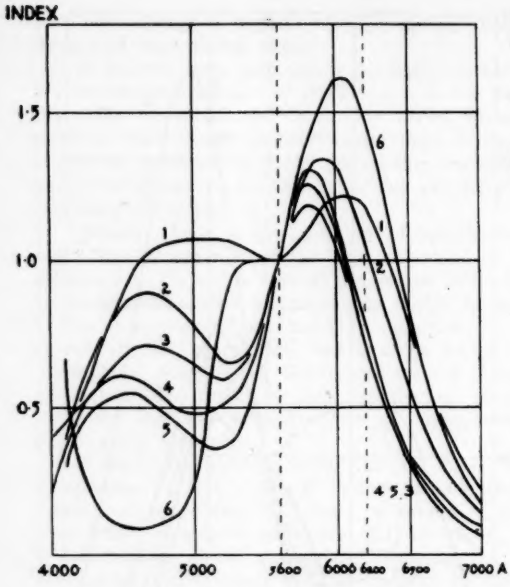

Fig. 2. Index for lamps of Fig. 1.

Index at λ = $\frac{\text{Energy per A. at } \lambda}{\text{Above ratio for full radiator of same } x.} \Big/ \frac{\text{energy per A. at 5600 A}}{}$

of the lamp divided by the redness of the full radiator. Incidentally the numerical value of the index is the same if luminance values are used instead of energy values.

For the yellow-green wave-length it is convenient to take 5,600 A because the standard tables for Planckian distributions at all temperatures are adjusted to a value of 100 at 5,600 A. Fig. 2 shows the index for the same lamps as in Fig. 1. An index is possible for any region of the spectrum, but clearly the red end is the most favourable, especially as the mercury lines can then be neglected. The red wave-length selected is 6,500 A, since for the lamps we are concerned with, the resulting index separates the "high efficiency" class easily from the "high fidelity" class, the latter being distinguished by a markedly better performance in visual colour-rendering tests, especially in the red region. The dividing line between the classes is conveniently placed at an index value of 0.5. Table 1 records the results for a variety of light sources. In the last column, values of the index for 6,200 A are given; this alternative is discussed below.

The two types of "White" lamp shown at the end of the table indicate the variations possible for a given chromaticity. One lamp has good red-rendering performance but somewhat low efficiency (A); the other shows the effect of phosphor modifications to give about 30 per cent. higher efficiency, but with reduced red output (B). A similar example is provided by the two "Peach" types, where the efficiency increase is smaller and the effect on colour rendering less marked. The other "high fidelity" types in the table are Northlight, Natural Daylight, and the U.S. "de luxe" lamps.

This index is intended to apply only to near-white fluorescent lamps of current types. It will give meaningless values for high-pressure mercury or sodium lamps, or for the present commercial green, blue, gold and red lamps.

The red wave-length of 6,200 A was at first thought to be suitable, especially as the index figure of 1 then divided fluorescent lamps into their appropriate classes, but in view of the probable use of new red phosphors with spectral emission in narrow

Table 1.

Lamp	Temp. of appropriate full radiator	6,500/5,600 ratio			6,200/5,600 ratio
		(A) Planck	(B) Lamp	B/A	B/A
	deg.K				
Northlight	6,500	0.831	0.648	0.78	1.18
Daylight	4,500	1.048	0.351	0.34	0.73
Natural Daylight	4,250	1.100	0.622	0.57	1.05
Warm White	3,250	1.430	0.474	0.34	0.76
U.S. Daylight	6,500	0.831	0.337	0.40	0.77
U.S. Cool White std.	4,500	1.048	0.352	0.33	0.68
U.S. Cool White de luxe	4,500	1.048	0.871	0.83	1.34
U.S. Soft White	4,250	1.100	0.913	0.83	1.38
U.S. White	3,500	1.309	0.420	0.32	0.70
U.S. Warm White std.	3,000	1.550	0.400	0.26	0.69
U.S. Warm White de luxe	3,000	1.550	1.138	0.73	1.03
White A	3,500	1.309	0.959	0.73	1.28
White B	3,500	1.309	0.391	0.30	0.72
Peach A	2,700	1.797	1.478	0.84	1.48
Peach B	2,700	1.797	0.726	0.41	0.90
Source B	4,900	0.987	1.011	1.03	0.97
Source C	6,750	0.816	0.839	1.03	0.96

bands[12] [13] it was found necessary to use 6,500 A instead. As an example, a commercial lamp containing magnesium arsenate phosphor proved to have a comparatively low emission at 6,200 A, but a large narrow peak in the region of 6,550 A. Therefore the index determined at 6,500 A (1.16, with a "pass limit" of 0.5) was a better guide than that at 6,200 A (0.94, with a "pass limit" of 1.0). A similar anomaly was that the standard sources B and C, and some varieties of natural daylight, owing to their peculiar s.e.d. curves, showed abnormally low values for the 6,200 A index, but at 6,500 A their high overall red content was properly expressed.

(3.2) Measurement of Red-Rendering Index

The index as already defined depends on knowledge of the lamp chromaticity, which is normally available, and of the s.e.d. curve, which also is generally published. The determination of the s.e.d. curve does not, in fact, need very complicated apparatus[14], and for the wave-lengths suggested the computation of mercury line energies is not necessary. As a practical alternative, the output of the two selected wave-lengths could be measured directly on a photocell of known spectral response, using narrow-band pass filters which might be of the interference type.

A further simplification would be to use all the red light beyond 6,500 A instead of a narrow band at 6,500 A, having in mind the usual sort of filter available for this region. To determine the results of this procedure, computations have been made assuming the use of Chance OR 1 glass to transmit the red band, and a metal dielectric filter to isolate a narrow yellow-green band at 5,600 A. The glass filter (2 mm. thick) has negligible transmission at 6,100 A, 74 per cent. at 6,500 A, and 90 per cent. beyond 6,800 A. The interference filter, of the third order, is assumed to have a peak transmission of about 20 per cent. at 5,600 A, a band width of about 100 A at half the peak

transmission, and negligible background transmission. Under these conditions the two "White" lamps previously discussed (Table 1) will theoretically give index numbers which, though of a different magnitude from those already quoted, stand in almost the same ratio as before. For the line measurements the ratio is $0.30/0.73 = 0.41$; for the filtered bands the ratio is $0.145/0.345 = 0.42$.

Lamps of other colours are found to give similar small changes of their index numbers relatively to each other by using the filtered bands, with a general tendency for "warmer" chromaticities to show proportionately lower numbers than by the line ratio, but without changes in the general separation into the good or poor red-rendering classes. Another example is furnished by "Daylight" and "Natural Daylight" lamps, whose indexes are in the ratio of 0.60 by the line method (Table 1), and 0.64 by the band method. The absolute index value for the separation into classes would be about 0.25 for the latter method.

The spectral sensitivity curve of a selenium cell, which would normally be used to make measurements of this kind, is such that its low red sensitivity is more than compensated by the width of the red transmission band compared with the narrow yellow-green band of the interference filter, at any rate for an equal energy spectrum. Thus with fluorescent lamps the responses of the photocell to the two bands will be of the same order. The method therefore appears to be feasible, provided there is adequate response to the photocell plus interference filter combination, since this will usually give the lower of the two readings.

The possibility of designing a meter has also been considered, in order to obtain the index when neither the s.e.d. curve nor the chromaticity is known. Such a meter would simplify lighting problems where, for example, the lamp is not the only factor involved, but the modifying effects of coloured walls have to be considered as well.

An incandescent source would be required and a series of colour filters, say of Chance OB 9 glass, to provide a range of chromaticities close to the black body locus. From these the nearest match to the test source could be selected and the appropriate value of A (Table 1) determined. Examination of the Table shows the index to be not very sensitive to changes in the black body temperature, and an approximate match would therefore be adequate. With a single photocell to respond to the light transmitted in turn by a pair of colour filters, as described above, the necessary data for the index would be obtained.

A more complex meter similar to the colour temperature meter[15], with two photocells connected in opposition, is also possible in principle. The chromaticity match would be employed to produce an alteration in the sensitivity of one of the cells, for example by a diaphragm or a circuit modification, and so affect the ratio of illuminations (5,600 : 6,500 A) giving a null reading. A calibrated diaphragm on one cell would provide for this null setting when the test lamp is viewed, and give a direct reading of the index. The main problem would evidently be to achieve sufficient sensitivity in the photocell plus filter combinations.

(4) Conclusion

The Red-Rendering Index offers a useful method of discrimination between different types of fluorescent lamp. It may be worth while applying similar partial solutions of the colour-rendering problem in other spectral regions than the red. The selection of wave-lengths will probably be somewhat arbitrary, but the overall complexity of the band method is avoided, and simple specifications may be laid down as a result.

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